LANGUAGE LEARNING
A Journal of Research in Language Studies
Language Learning ISSN 0023-8333

EMPIRICAL STUDY

Contrasting Explicit With Implicit Measures of Children's Representations: The Case of Segmental Phonology

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Current theories of phonological development make contrasting predictions about the role of vocabulary growth and orthographic knowledge in the emergence of segmental phonological representations. Testing these predictions in children is made difficult by the metacognitive nature of tasks used to assess phonological representations. In this study, we used novel tasks to measure the sensitivity of 88 children (3 years 2 months–5 years 7 months) to phonological segments, without requiring them to have any explicit awareness of the sounds in words. We contrasted these measures with measures requiring explicit segmental analysis of word forms. Results showed that, although explicit segmental analysis is related to letter–sound knowledge, tasks measuring implicit segmental sensitivity provide evidence of segmental phonology related to vocabulary growth and not mediated by orthography. Findings highlight the importance of tapping into the structure of children's phonological representations using tasks that minimize the requirement for explicit awareness.

Keywords phonological representations; lexical restructuring; phonological awareness; vocabulary; letter knowledge

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We thank the children, parents, and teachers who were involved in this study. This work was supported by the Economic and Social Research Council (ES/J500094/1).

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DOI: 10.1111/lang.12334

Introduction

Phonological representations are mental categories of the sounds in a language. It is important to understand the nature and development of phonological representations because they are linked to children's explicit knowledge of phonological elements—known as phonological awareness—and this explicit knowledge in turn has been linked to later reading success (Lonigan, Burgess, & Anthony, 2000). Given the importance of raising literacy levels, an understanding of the processes leading to mastery of reading and of how these break down in children with reading difficulties constitutes a priority for research (Department for Education, 2011; Hulme & Snowling, 2009). The extent to which the link between children's phonological knowledge and their later reading success may be mediated by their knowledge of letters has also been debated (Castles & Coltheart, 2004). Any comprehensive model of reading acquisition therefore needs to include a detailed account of how phonological representations develop and how they interact with children's explicit phonological awareness and their knowledge of letter–sound correspondences. Yet there is still little agreement about the structure of children's phonological representations and the way that they evolve over time.

Studying children's phonological representations is complicated by the fact that phonological-awareness tasks tend to require metacognitive awareness of sound structure. Measurements of children's explicit knowledge of their phonological representations (usually referred to as phonological awareness) can be contrasted with implicit measures of segmental sensitivity that do not require any explicit knowledge of the sound segments within words. This study is the first to directly contrast these two types of tasks to test the different predictions offered by current models of phonological development. As we defined above, phonological representations are mental representations of the sounds as they occur in words. Phonological awareness on the other hand is the term used to describe children's ability to reflect upon these representations and to manipulate the phonological segments stored within them. The terms phoneme, allophone, and phone are also used frequently in the literature. Phonemes are the abstract categories that linguists use to define minimal phonological contrasts between words (e.g., the change from *cat* to *pat* is characterized by the phonemic change /k/ to /p/); phones, on the other hand, are distinct speech sounds or gestures that need not be contrastive in terms of word meaning; allophones are a subtype of phone relating to different instances of a particular phoneme (e.g., the way that /k/ sounds in *cat*, which will be different from the way /k/ sounds in *back*). Related to the distinction between phones and phonemes are the terms phonemic representation and phonetically detailed representation. The former term refers to representations that store the sound structure of words as abstract phonemic categories; the latter refers to representations that contain detail about speech utterances at the phone level but are not necessarily stored as phonemic categories.

Key Accounts of the Development of Phonological Representation

Several key theoretical accounts of phonological development (summarized in Table 1) make predictions about the role of vocabulary and letter–sound knowledge in the development of segmental sensitivity and phonological awareness. Although these accounts assume the existence of abstract phonological representations, other frameworks also exist that assume exemplar-based representations (e.g., Bybee, 2002; Pierrehumbert, 2001, 2002).

The Accessibility Account

Some researchers have argued that young children's phonological representations are stored at a level of phonological detail similar to that of adults (e.g., Bailey & Plunkett, 2002; Ballem & Plunkett, 2005; Swingley, 2009; Swingley & Aslin, 2000) but that children can only consciously access the sound structure of words (e.g., in phoneme-awareness tasks) once they have developed the required metacognitive skills and letter knowledge needed to tap into the structure of their phonological representations (Liberman, Shankweiler, & Liberman, 1989; Rozin & Gleitman, 1977). Support for this account comes from studies in which infants have shown sensitivity to mispronunciations differing by only one phoneme in preferential-looking tasks (Bailey & Plunkett, 2002; Ballem & Plunkett, 2005) and visual-fixation tasks (Swingley, 2009; Swingley & Aslin, 2000). Researchers have argued that, because young children are sensitive to very small changes in pronunciation, their phonological representations must be stored at a fine level of detail. However, although these studies show convincing evidence of phonetically detailed representations, Swingley and Aslin pointed out that they did not allow the drawing of any conclusions about the level of segmentation of the representations—the extent to which the representations are stored in terms of abstract phonological segments.

If and when children's representations are stored phonemically remain important questions for empirical investigation. If phonemes are present from infancy, as proposed by the accessibility view, segmental-sensitivity tasks that circumvent the need for metacognitive awareness of sound structure should show fine-grained segmental structure in young children's phonological representations. One would also expect no unique relation between segmental sensitivity and either vocabulary or letter–sound knowledge, nor would one

Table 1 Summary of predictions made by the key theories of phonological development

		A unique relation between			Letter–sound knowledge is prerequisite for	
Theoretical account	Early competence on segmental sensitivity tasks	Segmental sensitivity and vocabulary	Segmental sensitivity and letter–sound knowledge	Phonological awareness and letter–sound knowledge	Phoneme-level phonological representations	Phoneme-level phonological awareness
Accessibility view[a]	Yes	No	No	Yes	No	Yes
Lexical restructuring model[b]	No	Yes	Unspecified	Unspecified	No	Unspecified
Psycholinguistic grain size theory[c]	No	Yes	Yes	Yes	Yes	Yes
Lexical restructuring model plus letters[d]	No	Yes	No	Yes	No	Yes
Current study	No	Yes	No	Yes	No	Yes

(Continued)

Table 1 Continued

Theoretical account	Early competence on segmental sensitivity tasks	A unique relation between: Segmental sensitivity and vocabulary	A unique relation between: Segmental sensitivity and letter–sound knowledge	A unique relation between: Phonological awareness and letter–sound knowledge	Letter–sound knowledge is prerequisite for: Phoneme-level phonological representations	Letter–sound knowledge is prerequisite for: Phoneme-level phonological awareness
Evidence from current study	Young nursery children are only just above chance on segmental sensitivity measures.	Segmental sensitivity measures are predicted by vocabulary but not age or letter–sound knowledge (Table 7).		Explicit segmental analysis is predicted by letter–sound knowledge but not age or vocabulary (Table 8).	Children with little letter–sound knowledge show sensitivity to phonemes on phoneme level segmental sensitivity tasks (Table 9).	Children with little letter–sound knowledge can blend phonemes but cannot explicitly tell you the sounds within a word (Table 9).

[a]Liberman, Shankweiler, & Liberman (1989), Rozin & Gleitman (1977); [b]Metsala & Walley (1998); [c]Ziegler & Goswami (2005); [d]Ventura, Kolinsky, Fernandes, Querido, & Morais (2007), Carroll (2004).

expect letter–sound knowledge to be needed for phoneme-level representations. One would, however, expect a unique relation between letter–sound knowledge and phonological awareness and for letter–sound knowledge to be a prerequisite for the emergence of phoneme-level phonological awareness given that the accessibility view proposes that experience with an orthography unlocks explicit access to the stored sound segments within words (Liberman et al., 1989; Rozin & Gleitman, 1977).

The Emergent Account

The second viewpoint—the emergent account—suggests that words are not initially stored in terms of phonemes and that adultlike phonological representations only emerge after a period of gradual lexical restructuring. Evidence for the emergent view comes from studies that detected qualitative differences in the way that children and adults classify words (see Metsala & Walley, 1998, for a review) and studies that showed representations becoming more segmentally detailed as children develop (Ainsworth, Welbourne, & Hesketh, 2016; Carroll & Myers, 2011; Metsala, 1997; Storkel, 2002). Proponents of the emergent view argue that, although infants have been shown to be sensitive to small phonetic differences, this does not require their lexicon to be phonemically organized (Bowey & Hirakis, 2006; Ziegler & Goswami, 2005). Ziegler and Goswami pointed out that the ability to distinguish between two phones is not the same as recognizing that different surface realizations of a given sound (allophones) can be categorized as one phoneme. In other words, although early infant discrimination studies provided evidence that children store phones corresponding to different phonemes distinctly (i.e., the /t/ in *ten* is stored in a way that makes it separable from the /b/ in *ben*), they did not address the question of whether incidences of the same phoneme occurring in different words are stored similarly (e.g., whether /b/ in *big* is stored in the same way as /b/ in *ben*). To settle the debate about whether phonemic representations are present from infancy or whether they emerge gradually over development, there is a need for measures that probe representation at the phoneme rather than the phone level. Under the umbrella of the emergent view, researchers have proposed three key variants.

Vocabulary Growth Drives the Segmentation of Children's Phonological Representations, Which Is a Prerequisite for Explicit Access to Phonological Segments

The lexical restructuring model (Metsala & Walley, 1998) suggests that vocabulary growth gradually stimulates the segmentation of phonological representations into onset–rime (where the onset is the initial consonant and the rime consists of the vowel and any remaining consonants within the syllable) and then phoneme-level representations. In this account, segmental representations are a prerequisite for explicit phonological awareness—in other words, children need to store representations of rime segments before they can access rime segments explicitly during rime-level phonological-awareness tasks. Similarly, children further need to segment representations into individual phonemes before they can access phonemic segments explicitly during tasks measuring phoneme-level phonological awareness. Evidence in support of this account has come from studies that showed a developmental shift in sensitivity from the global properties of phonological word forms to their subcomponents (Metsala, 1997; Metsala & Walley, 1998), along with studies providing evidence that words from dense phonological neighborhoods are more segmental than words from sparse neighborhoods (Garlock, Walley, & Metsala, 2001; Metsala, 1997). In the lexical restructuring model, this relation between neighborhood density and the segmentation of phonological representations is explained as words from more dense neighborhoods needing to be restructured first to keep them distinct from the large number of similar-sounding words in their neighborhood (Metsala, 1997; Metsala & Walley, 1998). The lexical restructuring model makes no specific predictions about the potential influence of orthographic knowledge on children's phonological representations or on children's explicit knowledge of them. However, it does suggest that phonological representations become phonemic through oral language experience alone, and therefore letter–sound knowledge is presumably not necessary for phoneme-level representations (Metsala & Walley, 1998).

Children's Phonological Representations Become Phonemic Only When They Have Learned the Mappings Between Graphemes and Phonemes

Psycholinguistic grain size theory (Ziegler & Goswami, 2005) shares the idea with the lexical restructuring model that phonological representations are gradually restructured to allow more efficient representation of similar-sounding words as children's vocabularies grow, but in this account, restructuring is not framed in terms of a shift from large to small representational components. Rather, the theory proposes that detail is added to children's representations at all grain sizes. Another key difference between the two accounts is that, although the lexical restructuring model proposes that phonemes emerge naturally through spoken language experience, grain size theory says that phonemic representation only emerges when children learn about phonemes explicitly, usually through their being taught grapheme–phoneme correspondences. It therefore predicts a unique relation between letter–sound knowledge and both the segmentation of phonological representations and phonological awareness, as well as a need for letter–sound knowledge before children can succeed on measures of both segmental-sensitivity and phonological-awareness tasks at the phoneme level. Evidence in support of this account comes from studies that showed that children lack the ability to count phonemes before they receive literacy instruction but develop the skill soon after literacy instruction begins (see Ziegler & Goswami, 2005, for a review). Analysis of children's spelling development (Treiman & Bourassa, 2000) and neuroimaging studies (Frith, 1998; Pattamadilok, Knierim, Kawabata Duncan, & Devlin, 2010) have also supported the idea of letter knowledge reshaping children's representations.

Lexical Restructuring Occurs in the Absence of Literacy, but Letter Knowledge Is Needed for Conscious Awareness of Phonemes

Ventura, Kolinsky, Fernandes, Querido, and Morais (2007) investigated the development of phonological representations by studying adults with varying levels of literacy. They found that illiterate adults may develop fine-grained segmental representations despite having limited letter knowledge, but they are not able to access these representations on phoneme-level phonological-awareness tasks in the same way as literate adults do. Other studies of illiterate populations have shown similar difficulties with phoneme-level phonological-awareness tasks (Adrian, Alegria, & Morais, 1995; de Gelder, Vroomen, & Bertelson, 1993), alongside normal performance on rime-level phonological-awareness tasks (de Gelder et al., 1993). In the developmental literature, Carroll (2004) also found phoneme-awareness measures to be dependent on letter–sound knowledge and suggested that children need to develop sensitivity to sound similarity at larger grain sizes (e.g., syllables and rimes) before they are able to develop full phoneme awareness. Together, results of these studies have suggested that although phonemes may emerge through children's spoken language experience alone at a representational level, children need to learn about letters to be able to consciously attend to the phonemic segments. Rime segments, on the other hand, appear to be accessible independently of letter knowledge. In this account, one would therefore expect no unique relation between letter–sound knowledge and segmental sensitivity but a significant unique relation between letter–sound knowledge and phonological awareness. In the interests of brevity, we will refer to this viewpoint as the lexical restructuring model plus letters, given that this account is an extension of the lexical restructuring model.

The Current Study

All three emergent theories predict that, as children learn more words, their lexicon is forced to represent words componentially to keep similar-sounding words distinct. Thus, one would expect segmental sensitivity to be uniquely related to vocabulary in each case. One would also expect children's performance on segmental-sensitivity measures to increase gradually rather than show full competency early on. Our study used novel measures of segmental sensitivity that did not require participants to have any explicit knowledge of phonological segments, as most phonological-awareness tasks do. The use of these novel measures might therefore have allowed us to get closer to the phonological representations themselves than would have been possible if we had used traditional phonological-awareness tasks. By contrasting measures of segmental sensitivity with measures of explicit segmental analysis—usually called phonological awareness—we were able to separate children's implicit sensitivity to phonological segments from their explicit awareness of these segments. This in turn allowed us to test the predictions made by the key theories of phonological development by investigating the following questions:

1. How are segmental sensitivity, phonological awareness, vocabulary, and letter–sound knowledge related to one another?
2. Do letter–sound mappings need to be learned before phoneme-level phonological representations emerge?
3. Does phonological awareness require letter–sound knowledge?

Method

Participants

We recruited 90 children from two mainstream primary schools in England with low and medium sociodemographic status as indexed by the percentage of free school meals, based on the schools' most recent inspection report (https://reports.ofsted.gov.uk). Children's ages ranged from 3 years 2 months to 5 years 7 months, with 48 children in nursery (prekindergarten) and 42 children in reception (kindergarten) classes. In England, most children enter school in nursery classes at age 3 to 4 years, but compulsory education begins with entry to reception classes at age 4 to 5 years. The gender balance was 46 boys and 44 girls with 26 and 20 boys in the nursery and reception groups, respectively. To be included in the study, participating children needed to have at least one English-speaking parent, to have no known history of speech or hearing problems (as reported by the teacher), and to not be on the special educational needs register for any behavioral or developmental concerns. We tested both the younger nursery group (age 3 years 2 months to 3 years 10 months, $n = 24$, 15 boys) and younger reception group (age 4 years to 4 years 7 months, $n = 22$, 9 boys) in the autumn term, and we tested the older nursery group (age 4 years to 4 years 5 months, $n = 24$, 11 boys) and older reception group (age 4 years 7 months to 5 years 7 months, $n = 20$, 11 boys) in the late spring/early summer terms. We chose these groupings to capture performance at different stages in the participants' developmental and educational journeys. Although there was substantial overlap between the ages of the older nursery and younger reception groups, they had received differing amounts of literacy instruction. In England, phonological awareness activities begin in nursery classes (ages 3 to 4 years), following a systematic synthetic phonics program up until Year 2 (ages 6 to 7 years). Younger reception children are therefore more experienced in both phonological awareness and letter–sound mapping activities than older nursery children.

We also recruited an adult control group to confirm the construct validity of the novel measures. We wanted to check that literate adults, who presumably have detailed, fine-grained representations, do in fact score highly on the measures of segmental sensitivity. The adult sample consisted of 74 undergraduate students. We excluded adult participants if English was not their first language or if they had any diagnosed dyslexia or hearing difficulties. We tested the adult group on the four segmental-sensitivity measures and the rhyme task. We did not test them on the blending, phoneme-isolation, or letter–sound-knowledge tasks because we assumed that they would perform at ceiling on these measures. We also did not test them on the vocabulary measures, which were suitable for children only.

Procedure

We tested the participating children in a quiet room in their schools over 5 to 10 sessions, depending on their age and attention span. We audio-recorded all tasks requiring a verbal response from the participants. We gave no corrective feedback except for one training item at the beginning of each task and for the expressive vocabulary and letter–sound knowledge tests, which did not have any training items. We gave participants general praise and stickers as encouragement regardless of their performance on the tasks. For all the segmental-sensitivity and segmental-analysis measures, we used two sets of item orders to control for order effects. In each age group, we assigned participating children randomly to either set. The order in which we delivered the tasks was kept constant across all participants. We did this to ensure that the explicit-segmental-analysis tasks always followed the segmental-sensitivity tasks. If participants had carried out the more explicit-segmental-analysis tasks first, this might have impacted their performance on the sensitivity tasks due to the increased salience of the segments accessed in the analysis tasks.

Materials

We chose pictures that would be familiar to young children. Almost all of the lexical items (98%) that we used are present in Storkel and Hoover's (2010) database, which was drawn from corpora of kindergarten and first-grade children (Moe, Hopkins, & Rush, 1982). To make sure that children identified the pictures correctly, we asked them to name the pictures at the beginning of each trial and provided the correct name where it was necessary. In all the multiple-choice tasks, we matched the distracters listwise based on frequency and, using Storkel and Hoover's online calculator, on two measures of phonotactic probability: (a) positional segment average—how often the segments within a word occur in that position within other words and (b) biphone average—the frequency of pairs of sound segments. The full stimulus list, including matching characteristics, is available in Appendix S1 in the Supporting Information online.

Measures of Segmental Sensitivity

We devised four segmental measures that measured segmental sensitivity at both the onset–rime and phoneme levels. A summary of all tasks is provided in Appendix S2 in the Supporting Information online. The first three tasks involved the participating children making similarity classifications and shared the same rationale. Given the inherent noise associated with similarity-judgment tasks (e.g., Kessler, 2005), we believed it important to include multiple measures. The first two tasks involved comparison of pseudowords and real words. In the mispronunciation-conflict task, the participants heard two pseudowords and were asked to decide which one was closest to the real target word. In the mispronunciation-reconstruction task, participants were asked to choose which real word most closely resembled a pseudoword stimulus. In the third task—pseudoword similarity—participants had to decide which pseudoword sounded the most like another given pseudoword. We used pseudowords in these tasks following Carroll and Myers (2011), who noted that nonword measures provide a potentially useful way to tap into the development of new phonological representations.

For each task, participating children were asked to compare auditory consonant–vowel–consonant (CVC) stimuli in terms of how similar they sounded. In each trial, the target response was a word or pseudoword that shared two phonemes with the stimulus (e.g., *tet–ten*) and the closest distracter was a word or pseudoword that shared only one phoneme with the stimulus but was matched in terms of global similarity (e.g., *tet–tape*; see below for further details on global similarity matching). The idea here was that if participants chose the closest segmental match more often than the globally matched distracter, then we could infer that they were sensitive to the number of shared segments over and above how similar the words or pseudowords were in terms of overall sounds likeness. Sensitivity to shared segments in turn suggests phonological representations are segmented at least at the grain size of those segments. In other words, if children are sensitive to shared rimes, then their representations must be segmented at least at the onset–rime level. If children are sensitive to shared phonemes within words, this suggests a finer-grained phonemic representation of those words.

The three tasks contained two types of items measuring segmental sensitivity at either the rime or phoneme levels. Although rime-level items involved two shared phonemes in the rime position (e.g., *tain–rain*), phoneme-level items had two shared phonemes in body position (e.g., *tet–ten*). We assumed that, although rime items can be completed with representations that are segmented at the rime level only (by comparing the rime segments as a whole), a finer-grained phonemic representation is needed for phoneme-level items where the rime segment is disrupted. Studies that have emphasized the developmental primacy of the rime in English have supported this assumption (Metsala & Walley, 1998; Ziegler & Goswami, 2005) and have suggested that children's representations are restructured from whole-word templates, to onset–rime, and then to phonemic representations (Metsala & Walley, 1998; Treiman & Zukowski, 1991).

In the similarity-based measures, we matched the closest distracter (or only distracter in the case of the two-choice tasks) to the segmental response in terms of global similarity. For example, when we asked participating children whether *nig* or *teg* sounded the most like *pig* (although *nig* is segmentally closer to *pig*, it shares two rather than one phoneme with *pig*; *teg* is equally close to *pig* in terms of global similarity or overall sounds likeness). We operationalized global similarity using adult ratings collected by Singh and Woods (1971) and Singh, Woods, and Becker (1972). We calculated scores of how dissimilar the standard was from the target and the distracters using the same concatenative method adopted by Treiman and Breaux (1982) and others (Byrne & Fielding-Barnsley, 1993; Carroll & Snowling, 2001). For example, the dissimilarity score between the words *pin* (pronounced /pɪn/) and *bed* (pronounced /bɛd/) is

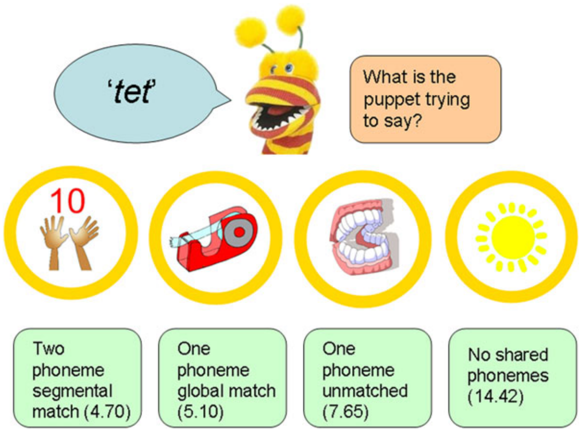

Figure 1 Measure of segmental sensitivity. Sample phoneme-level item from the mispronunciation-reconstruction task. Numbers in parentheses show the global similarity distance between the stimulus and each response choice. [Color figure can be viewed at wileyonlinelibrary.com]

the dissimilarity of /p/ and /b/ (3.9) plus the dissimilarity of /ɪ/ and /ɛ/ (2.22) plus the dissimilarity of /n/ and /d/ (4.8), giving a total dissimilarity score of 10.92. Although this metric represents only an approximation of global similarity in that it fails to take into account the effects of coarticulation and the incremental nature of word recognition, previous studies using this metric have provided support for its validity as an appropriate proxy. For example, Byrne and Fielding-Barnsley found that performance on a phoneme-invariance task was dramatically reduced when common phoneme relations were confounded with global similarity (as measured through this metric). Furthermore, we found the level of global similarity to be proportional to the likelihood of a child making that response. Similarly, Carroll and Snowling found that global distractors matched according to this metric had a greater confounding effect than semantic or unrelated distractors.

Mispronunciation Reconstruction (12 Items)

Participating children heard a puppet mispronounce a word and were then asked to guess which picture the puppet was trying to say—which picture the word sounded the most like (see Figure 1). For example, the puppet said *tet* (spoken live by the researcher), and the participants chose whether he was trying to say *ten*, *tape*, *teeth*, or *sun*.

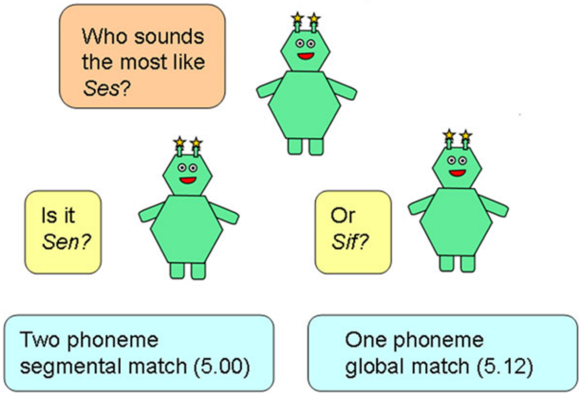

Figure 2 Measure of segmental sensitivity. Sample phoneme-level item from the pseudoword-similarity task. Numbers in parentheses show the global similarity distance between the stimulus and each response choice. [Color figure can be viewed at wileyonlinelibrary.com]

Pseudoword Similarity (16 Items)

Participating children were asked which of two pseudoword alien names (spoken live by the researcher) sounded the most like a third pseudoword name (see Figure 2). For example, "Which one sounds the most like *Ses*? Is it *Sen* or *Sif*?" This task was an adaptation of the common phoneme-classification task developed by Treiman and Breaux (1982) and Treiman and Baron (1981). Although our task had a rationale similar to the original task, we reduced the working memory demands by asking participants to choose one name rather than the most similar pair of names. Our task also took a more continuous approach to phonemic similarity, with the two choices sharing one and two phonemes rather than one and no phonemes, to make it more comparable with the other tasks in the battery.

Mispronunciation Conflict (16 Items)

In this novel task, participating children heard three onscreen aliens attempt to say a word while the target picture was shown on the laptop screen and were first asked to choose which of the three aliens had said the word correctly. We included this part of the task to check that the participants were able to recognize the correct form of the word as being distinct from the mispronunciations. They then listened to the two aliens who had said the word incorrectly again and were asked, "Which one said it the best? Which one sounded the most like it?" (see Figure 3). For example, participants chose whether *nig* or *teg* sounded most

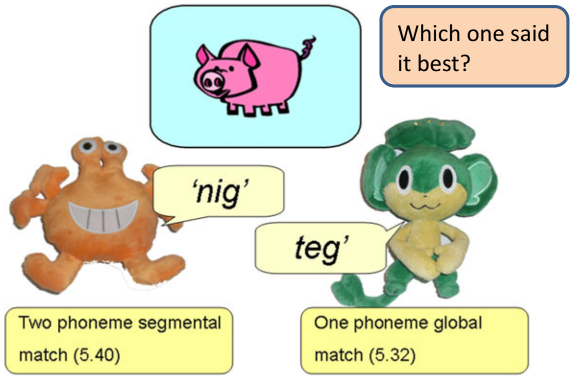

Figure 3 Measure of segmental sensitivity. Sample rime-level item from the mispronunciation-conflict task. Numbers in parentheses show the global similarity distance between the stimulus and each response choice. [Color figure can be viewed at wileyonlinelibrary.com]

like *pig*. The researcher had prerecorded the audio stimuli in a sound-attenuated booth and presented them on a laptop to make the aliens appear to be saying the words. To provide consistency of pronunciation, the same researcher who had prerecorded the audio stimuli administered all tasks—some of which involved live presentation of stimuli—with all participants.

For each of the similarity-classification tasks, participating children scored one point for each item where they chose the segmental response—the word or pseudoword that shared the most phonemes with the stimulus—and zero points for all other responses. There was no correct response in the sense that a global response (i.e., the word or pseudoword that shared only one phoneme with the stimulus but was globally similar) was an equally valid answer to the question. We scored the task in this way to allow us to measure participants' sensitivity to segmental similarity while holding global similarity constant.

Incomplete Word (16 Items)

Participating children heard an onset spoken live by the researcher, and then they were asked to choose from a set of four pictures the picture that the puppet wanted, where the target picture was of a word sharing the onset spoken by the puppet (see Figure 4). For rime-level items, the stimulus was a single consonant (e.g., /b/ with target picture *boat*). Although strictly speaking, these items would be more accurately labeled as onset items rather than rime items, we kept the rime label to make the distinction between items that could be completed with onset–rime level of representation only and phoneme-level items that

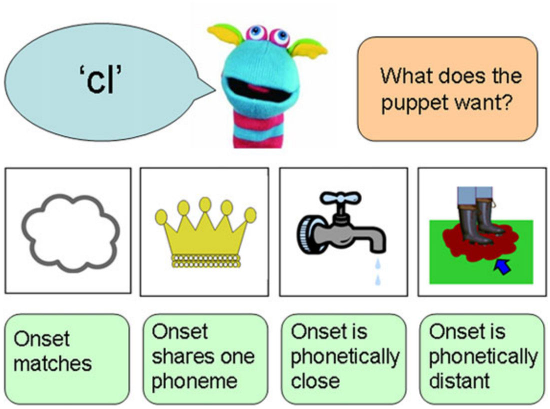

Figure 4 Measure of segmental sensitivity. Sample phoneme-level item from the incomplete-word task. [Color figure can be viewed at wileyonlinelibrary.com]

require finer-grained phonemic representations. On this task, phoneme-level items required participants to link a consonant cluster to a word (e.g., /kl/ *cloud*), where the closest distracter began with a cluster sharing the same initial consonant (e.g., *crown*). The rationale here was that although children can link /b/ to *boat* when their phonological representation for *boat* is segmented at the onset–rime level only, children will only be able to distinguish between the /kl/ in *cloud* and the /kr/ in *crown* if they have a finer-grained phonemic representation of these words. Although this task was superficially similar to the phoneme-identification task (Elbro & Petersen, 2004) that measured children's explicit phonological awareness, there was a key difference that made it a measure of segmental sensitivity rather than one of phonological awareness. Unlike phonological-awareness tasks, the incomplete-word task did not ask participants to explicitly reflect on the sounds in words; rather, they were asked to simply guess what the puppet wanted after they had heard it say a sound.

Each of the segmental-sensitivity tasks shared the key characteristic that they did not require participants to have any explicit awareness of the individual segments within words. Although the tasks did have a metacognitive element in that participants were asked to make a conscious decision for each item, the measures can be classified as implicit in the sense that the stimuli and instructions did not refer to explicit phonological knowledge. By asking participants to make a sounds-like judgment in the case of the three similarity-based judgment tasks or an associative judgment in the incomplete-word task rather than an explicitly phonological judgment, we aimed to probe participants' sensitivity to phonological segments without requiring them to have any explicit awareness of the structure of these representations. These tasks can be framed in a neural network paradigm where the judgments, although made consciously, are informed at an implicit level by activations in children's phonological representations that occur when they are presented with a particular stimulus (cf. Swingley & Aslin, 2000).

Measures of Explicit Segmental Analysis

Rhyme (8 Items)

Participating children were shown four pictures (e.g., of the sun, rain, a pan, a coat) and were asked which one rhymed with a given stimulus spoken live by the researcher (e.g., "Which one rhymes with run?"). The participants did not hear the choices aloud but, as with all other tasks involving pictures, were asked to name each picture at the beginning of each trial to check if they had recognized the picture correctly.

Blending (16 Items)

Participating children heard the prerecorded voice of a robot say either an onset and a rime (e.g., *t–en*) or three individual phonemes (e.g., *t–e–n*) and were asked to select the corresponding picture.

Phoneme Isolation (16 Items)

Participating children were shown a picture and asked to say the sounds in the word (e.g., *c–a–t* if shown a picture of a cat). To avoid unnecessary testing, if participants were not able to isolate any of the sounds in eight consecutive words, we stopped testing and assumed that these participants would have scored 0 on all remaining items. This criterion applied to 19 participants.

In contrast to the segmental sensitivity measures, each of the three analysis measures required participants to have some explicit knowledge of the phonological structure of words. In the rhyme task, participants needed to understand that monosyllabic words can be separated into an onset and a rime and that when words share the same rime segment, they are said to rhyme. In the blending task, participants needed to understand that they could reassemble a word from its constituent phonemes. In the phoneme-isolation task, participants needed to know that words can be segmented into individual phonemes.

Background Language Measures

Letter–Sound Knowledge

Participating children were shown a grapheme—a letter or group of letters—and were asked what sound it represented. The graphemes were presented in order of difficulty as indexed by the order in which the Letters and Sounds framework (Primary National Strategy, 2007) recommends that they be taught. We halted testing if participants failed to say the sounds for eight consecutive letters and scored these participants as knowing the number of letters answered correctly up to that point. This criterion applied to 44 children. The test contained 35 graphemes in total. In this article, when we use the term letter–sound knowledge, we refer broadly to all grapheme–phoneme correspondences (e.g., including the mappings for digraphs like *sh*–/ʃ/) and not just to the mappings between single letters and sounds.

Vocabulary

We measured expressive and receptive vocabulary using the Renfrew Word Finding Vocabulary Test (Renfrew, 1995) and the British Picture Vocabulary Scale (Dunn et al., 2009), respectively. We slightly adapted the standardized procedure for the British Picture Vocabulary Scale, such that all participants started at Set 1 regardless of their age so that we could compare raw scores between age groups.

Results

Data Screening

Data screening showed that one adult participant had extreme outlier scores for three of the six tasks—scores with values more than 1.5 times the interquartile range below the first quartile. We removed this participant's scores prior to analysis. We found no extreme outliers in the child data, but two child participants did not attempt one or more of the tasks. We also excluded the scores from these two participants listwise from the analyses that follow, with the exception of reliability estimates for the individual scales where we included all participating children who had completed that scale.

We calculated reliability estimates for the segmental sensitivity and analysis measures using the glb.algebraic (i.e., greatest lower bound) function in the psych package (Revelle, 2018) in R (R Core Team, 2018). We used the greatest lower bound (Ten Berge & Sočan, 2004; Woodhouse & Jackson, 1977) rather than the commonly cited Cronbach's alpha (Cronbach, 1951), following widespread concerns around the latter's applicability in most realistic psychometric situations (McNeish, 2018; Sijtsma, 2009; Trizano-Hermosilla & Alvarado, 2016). We did not calculate measures of internal consistency for the letter–sound knowledge and vocabulary measures given that we had designed them to increase in difficulty as the test progressed and that different participants completed different numbers of items. For the phoneme-isolation task, we

Table 2 Reliability estimates for segmental sensitivity and explicit segmental analysis tasks

Task	Greatest lower bound
Segmental sensitivity	
Incomplete word	.92
Mispronunciation conflict	.76
Mispronunciation reconstruction	.73
Pseudoword similarity	.76
Explicit segmental analysis	
Rhyme	.73
Blending	.95
Phoneme isolation	.999

excluded from the reliability analysis participants for whom we had halted testing early due to a 0 score after eight items. We found reliabilities (Table 2) to be high for the blending, phoneme-isolation, and incomplete-word tasks. The reliability estimates for the mispronunciation-conflict, mispronunciation-reconstruction, and pseudoword-similarity tasks were somewhat lower (although still $> .70$). The fact that the reliability estimates were generally higher for the explicit-segmental-analysis tasks than for the segmental sensitivity tasks reflects the relative difficulty in measuring implicit sensitivity compared to measuring explicit knowledge (e.g., Stadler, 1997).

Summary of Children's Performance

The mean scores for the segmental-sensitivity and explicit-segmental-analysis tasks (summarized in Figures 5 and 6) show participating children to be significantly above chance on all of the multiple-choice tasks from the older nursery group upwards. This indicates that participants age 4 years to 4 years 5 months in the second half of their nursery-school year were already showing sensitivity to shared segments in words and had some explicit awareness of these segments. We conducted an additional analysis on the mispronunciation-reconstruction scores to check if the youngest group was indeed showing sensitivity to segments or if this group was scoring above chance because of the four-choice nature of the task. It would, for example, have been possible for participants to split their responses equally between the segmental choice and the global choice, yet still to score above chance. A binomial test comparing segmental responses to global responses showed that this was not the case, demonstrating that the younger nursery participants chose the segmental response significantly

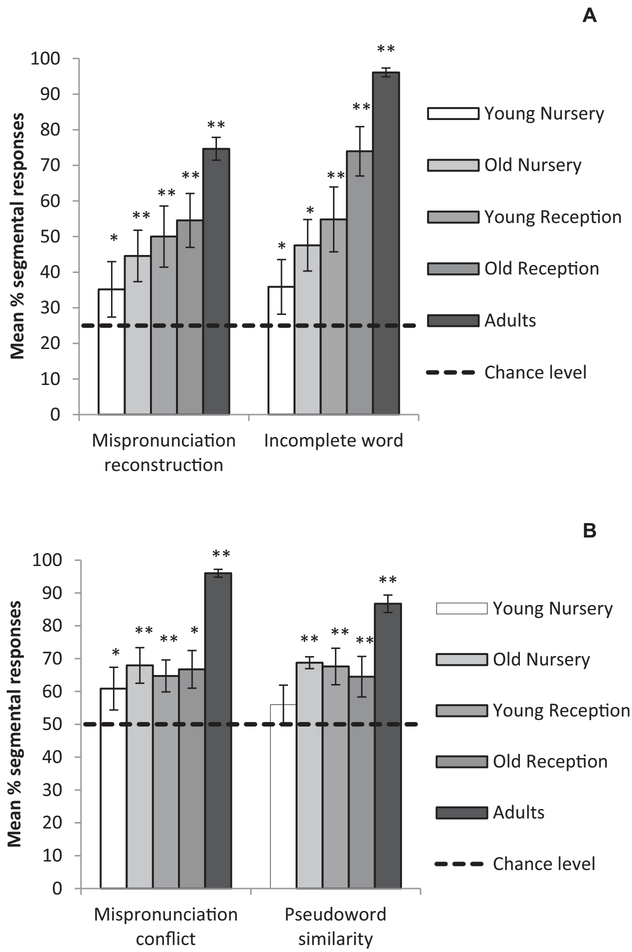

Figure 5 Performance on segmental sensitivity measures with a chance level of (a) 25% and (b) 50%. Error bars represent 95% confidence intervals. Asterisks indicate performance significantly above chance. *$p < .05$. **$p < .001$.

more than the global response ($p = .031$). The response patterns for each cohort (Figure 7) suggested gradual migration of responses away from phonemically unrelated responses to more phonemically similar responses and indicated that participants' judgments were also affected by global similarity.

For the phoneme-isolation task, which was a free-choice task, we chose a success threshold of 42% following an inspection of the histogram for phoneme-isolation performance, which showed a bimodal distribution centered around

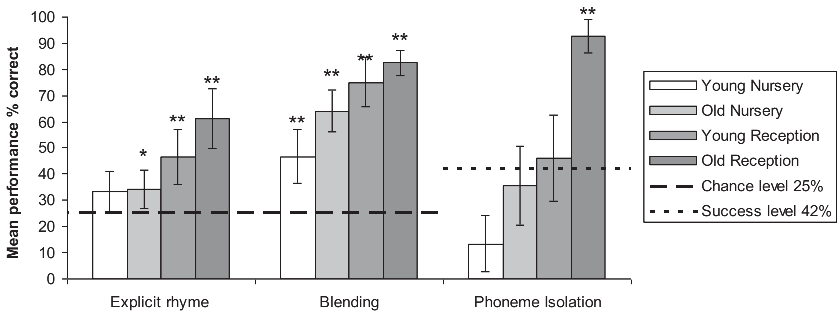

Figure 6 Performance on measures of explicit segmental analysis. Error bars represent 95% confidence intervals. Asterisks indicate performance significantly above chance. $*p < .05$. $**p < .001$.

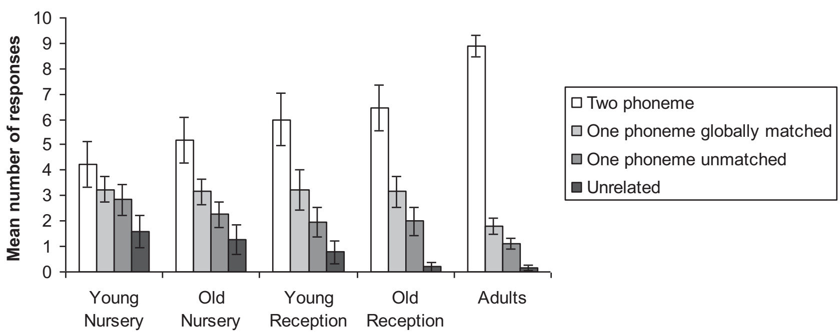

Figure 7 Participating children's response profiles for the mispronunciation-reconstruction task across the four age groups with adult performance included for comparison. Error bars represent 95% confidence intervals.

this point. Participating children did not succeed on this task before entering the reception year, and they only achieved high levels of performance in the second half of the reception year. Nursery participants age 3 years 2 months to 3 years 10 months, whom we tested at the beginning of the school year, demonstrated limited ability on the explicit-segmental-analysis tasks, scoring only above chance on the blending task, and knew very few letter–sound correspondences ($M = 3$ letter–sounds known, $SD = 6$), yet they scored just above chance on three out of four of the segmental-sensitivity tasks. This suggested that some sensitivity to shared segments may develop before children learn about letters and become consciously aware of phonological segments. Segmental-sensitivity performance of the youngest participants was, however, only just above chance and was below ceiling even for the older reception participants.

Table 3 Means and standard deviation values (in parentheses) for group performance on measures of letter–sound knowledge and vocabulary

Class level	Letter–sound knowledge	Receptive vocabulary	Expressive vocabulary
Younger nursery	2.57 (5.53)	47.17 (17.76)	17.85 (7.37)
Older nursery	7.13 (8.77)	56.78 (17.64)	21.35 (6.29)
Younger reception	13.36 (9.78)	59.77 (13.32)	24.73 (4.28)
Older reception	29.25 (3.37)	70.35 (11.90)	27.95 (5.81)

Performance for the adult participants across all segmental-sensitivity measures was high, confirming that the sensitivity tasks do elicit a segmental response in literate adults, who presumably have fine-grained phonological representations. Table 3 provides a summary of child participants' performance on the measures of letter–sound knowledge and vocabulary.

Effect of Age on Segmental Sensitivity

We conducted a one-way between-subjects analysis of variance to compare the effect of cohort (class group) on segmental sensitivity. There was a significant effect for cohort for each of the four sensitivity tasks: incomplete word, $F(4, 156) = 81.64$, $p < .001$, mispronunciation conflict, $F(4, 156) = 70.38$, $p < .001$, mispronunciation reconstruction, $F(4, 156) = 29.44$, $p < .001$, and pseudoword similarity, $F(4,156) = 33.99$, $p < .001$. We conducted post hoc pairwise comparisons with Bonferroni adjustment to see if there were significant differences in performance on each task from one cohort to the next. For the incomplete-word task, there was no significant difference between performance of the younger and older nursery groups ($p = .18$, $d = 0.50$, 95% confidence interval [CI] [–0.09, 1.08]). However, we found significant differences between the younger nursery and younger reception groups ($p = .002$, $d = 1.06$, 95% CI [0.43, 1.68]), the younger reception and older reception groups ($p = .003$, $d = 0.90$, 95% CI [0.25, 1.53]), and the older reception and adult groups ($p < .001$, $d = 2.15$, 95% CI [1.56, 2.73]).

For the mispronunciation-conflict task, there were no significant differences between the younger and older nursery groups ($p = .36$, $d = 0.45$, 95% CI [–0.13, 1.04]), the older nursery and younger reception groups ($p = 1.00$, $d = –0.02$, 95% CI [–0.08, 0.04]), or the younger reception and older reception groups ($p = 1.00$, $d = 0.16$, 95% CI [–0.44, 0.77]). There was a significance difference, though, between older reception and adult performance on this task ($p < .001$, $d = 3.35$, 95% CI [2.65, 4.04]).

For the mispronunciation-reconstruction task, we found no significant differences between the younger and older nursery groups (p = .69, d = 0.50, 95% CI [–0.09, 1.09]), the older nursery and younger reception groups (p = 1.00, d = 0.28, 95% CI [–0.31, 0.87]), or the younger reception and older reception groups (p = 1.00, d = 0.24, 95% CI [–0.37, 0.84]). There was, however, a significant difference between the younger nursery group and the younger reception group (p = .048, d = 0.75, 95% CI [0.14, 1.35]) and between the older reception group and the adults (p < .001, d = 1.20, 95% CI [0.68, 1.72]).

For the pseudoword task, there was a significant difference between the younger nursery and older nursery groups (p = .01, d = 0.85, 95% CI [0.24, 1.45]) and between the older reception and adult groups (p < .001, d = 1.90, 95% CI [1.33, 2.46]). There was no significance difference in pseudoword performance between older nursery and younger reception groups (p = 1.00, d = –0.08, 95% CI [–0.66, 0.51]) or between younger reception and older reception groups (p = 1.00, d = –0.23, 95% CI [–0.83, 0.38]). A full breakdown of all pairwise comparisons is provided in Appendix S3 in the Supporting Information online.

Dimensionality of the Measurement Battery

To investigate the relationships between the key variables implicated in theories of phonological development, we conducted correlational analyses (see Table 4) that we followed with a reduction of the battery of scores into a series of factors using factor analysis. We entered the seven phonological measures into a factor analysis using maximum likelihood extraction with varimax rotation. We chose varimax rotation for its ability to simplify interpretation of factor structure. Forcing the factors to be orthogonal often allows extraction of factors that represent only a small number of variables, with each variable loading highly onto one factor or a small number of factors (Abdi & Williams, 2010). In this way, we attempted to separate the variance in the measures related to segmental sensitivity from those related to explicit analysis.

Two factors emerged following application of Kaiser's criterion, where only factors with eigenvalues greater than 1 are retained (Kaiser, 1960). The amount of variance in the measures explained by the factors was 55%. Applying a significance threshold of .45 to the loadings in the rotated matrix (Table 5), we found that the loadings roughly divided the measures into the two predicted types: Explicit Segmental Analysis (Factor 1) and Segmental Sensitivity (Factor 2). All of the segmental-sensitivity measures loaded more highly onto Factor 2 than onto Factor 1 (except for the incomplete-word task), and they all

Table 4 Correlation matrix for all task variables plus age

Variables	1	2	3	4	5	6	7	8	9	10
1 Mispronunciation reconstruction	–	.43**	.38**	.44**	.17	.39**	.40**	.31**	.38**	.19
2 Pseudoword similarity	.47**	–	.44**	.28**	.11	.23*	.31**	.23*	.31*	.13
3 Mispronunciation conflict	.40**	.46**	–	.44**	–.03	.36**	.33**	.31**	.26*	.20
4 Incomplete word	.54**	.34**	.45**	–	.18	.55**	.65**	.35**	.36**	.52**
5 Rhyme	.30**	.19	.04	.35**	–	.19	.29**	.31**	.34**	.36**
6 Blending	.51**	.30**	.38**	.67**	.36**	–	.60**	.34*	.24*	.39**
7 Phoneme isolation	.53**	.36**	.34**	.75**	.47**	.73**	–	.40**	.34**	.73**
8 Receptive vocabulary	.43**	.29*	.34*	.50**	.44**	.50**	.57**	–	.68**	.43**
9 Expressive vocabulary	.49**	.37**	.30**	.52**	.47**	.45**	.55**	.75**	–	.38**
10 Letter–sound knowledge	.40**	.24*	.24*	.67**	.53**	.62**	.85**	.60**	.61**	–
11 Age	.38**	.20	.14	.50**	.41**	.54**	.64**	.46**	.51**	.76**

Note. Partial correlations, controlling for age, are presented above the diagonal, and bivariate correlations are presented below the diagonal. $^{*}p < .05$. $^{**}p < .01$.

Table 5 Rotated factor matrix loadings for segmental sensitivity and explicit segmental analysis tasks

Task	Factor 1	Factor 2
Segmental sensitivity		
Mispronunciation reconstruction	.44	.50
Pseudoword similarity	.20	.55
Mispronunciation conflict	.10	.79
Incomplete word	.70	.46
Explicit segmental analysis		
Rhyme	.53	.02
Blending	.71	.37
Phoneme isolation	.86	.32
R^2	.32	.23

Note. Shading indicated loadings greater than .45.

Table 6 Correlations between all derived variables and age

Variables	1	2	3	4
1 Segmental Sensitivity	–			
2 Explicit Segmental Analysis	.18	–		
3 Vocabulary	.39**	.59**	–	
4 Letter–Sound Knowledge	.25*	.85**	.64**	–
5 Age	.18	.66**	.52**	.76**

Note. $^{*}p < .05$, one-tailed; $^{**}p < .01$, two-tailed.

had Factor 2 loadings greater than .45. Conversely, all three explicit-segmental-analysis tasks loaded more highly onto Factor 1 than onto Factor 2 (and with loadings greater than .45). This supported the idea that we were measuring two different levels of phonological knowledge. Given that the factor loadings were largely consistent with the distinction made between the two types of measures, we interpreted Factor 1 and Factor 2 as representing explicit segmental analysis and segmental sensitivity, respectively.

We also generated a vocabulary factor by entering the two measures of vocabulary into a principal components analysis, thus creating a weighted average of the expressive and receptive vocabulary scores. The principal component loadings for the British Picture Vocabulary Scale and word finding measures were both equal to .94, $R^2 = .88$. The letter–sound knowledge score remained as a standalone variable. In this way, we were able to condense the data into four key factor variables: Segmental Sensitivity (children's implicit sensitivity to the segmental structure of their phonological representations), Explicit Segmental Analysis (children's conscious awareness of the segmental structure of their phonological representations), Vocabulary, and Letter–Sound Knowledge. We carried out a correlational analysis to investigate the relationships between the four key variables as well as between them and age (Table 6). All correlations were significant ($p < .05$), apart from the correlations between Segmental Sensitivity and age ($r = .18$, $p = .086$) and Segmental Sensitivity and Explicit Segmental Analysis ($r = .18$, $p = .099$).

Relationships Between Segmental Sensitivity, Segmental Analysis, Age, Vocabulary, and Letter–Sound Knowledge

To further investigate the nature of these interrelations and to test the predictions made by the different theories of phonological development (see Columns 2 to 4 in Table 1), we created two regression models. In the first regression model, we entered Segmental Sensitivity as the outcome variable and entered

Table 7 Regression model with Segmental Sensitivity as the outcome variable and Vocabulary, Letter–Sound Knowledge, and age as predictors

Variables	*b*	*SE b*	β	*p*	Partial correlations
Constant	0.27	0.89		.77	
Vocabulary	0.33	0.11	.39	.004	.30
Letter–Sound Knowledge	0.003	0.01	.04	.83	.02
Age	–0.006	0.02	–.05	.76	–.03

Table 8 Regression model with Explicit Segmental Analysis as the outcome and Vocabulary, Letter–Sound Knowledge, and age as predictors

Variables	*b*	*SE b*	β	*p*	Part correlations
Constant	–1.04	0.56		.07	
Vocabulary	0.06	0.07	.06	.42	.05
Letter–Sound Knowledge	0.06	0.007	.77	< .001	.45
Age	0.006	0.01	.05	.60	.03

age, Vocabulary, and Letter–Sound Knowledge simultaneously as predictors. In the second regression model, we entered Explicit Segmental Analysis as the outcome variable and entered the other three variables—age, Vocabulary, and Letter–Sound Knowledge—simultaneously as predictors. The use of multiple regression in this way allowed us to investigate the relative influence of Vocabulary and Letter–Sound Knowledge on measures of Segmental Sensitivity and Explicit Segmental Analysis. We also included age as a predictor in both models in an attempt to isolate the influence of Vocabulary and Letter–Sound Knowledge on Segmental Sensitivity and Explicit Segmental Analysis independent of general age-dependent factors (e.g., attention span, ability to follow instructions, etc.).

In the first model, we found that Vocabulary was a significant predictor of Segmental Sensitivity whereas age and Letter–Sound Knowledge were not (see Table 7). The model yielded an adjusted R^2 of .12 ($p = .003$). In the second model, we found Letter–Sound Knowledge was a significant predictor of Explicit Segmental Analysis whereas age and Vocabulary were not (see Table 8). This model explained a greater proportion of the variance with an adjusted R^2 of .71 ($p < .001$).

To establish whether children need letter–sound knowledge before sensitivity to phonemes emerges, we divided participating children into two groups with a threshold of fewer than three letters known assigned to the

Table 9 Percentage of participating children in the low letter knowledge group (< three letters known, $n = 36$) who succeeded on each task of the segmental sensitivity and explicit segmental analyses

	Items		
Task[a]	All items	Rime level	Phoneme level
Segmental sensitivity			
Mispronunciation reconstruction (25%)	61	56	72
Pseudoword similarity (50%)	61	44	56
Mispronunciation conflict (50%)	69	64	44
Incomplete word (25%)	53	56	36
Explicit segmental analysis			
Rhyme (25%)	50	50	–
Blending (25%)	86	81	72
Phoneme isolation (42%)	6	6	0

Note. [a]Percentage of success threshold is given in parentheses.

low-letter-knowledge group. We also grouped participants based on their performance on each of the segmental-sensitivity measures. We established three different classifications corresponding to performance: overall on the task, on rime-level items, and on phoneme-level items. The rationale for examining performance on items measuring segmental sensitivity at the rime versus the phoneme level separately was that theoretical accounts differ in terms of whether letter–sound knowledge is needed to reach the most fine-grained level of representation—the phoneme. In each case, the classification threshold represented the chance level. Table 9 shows that the majority of participants who knew fewer than three letters was above chance overall on all of the segmental-sensitivity tasks, suggesting that letter–sound knowledge may not be needed for segmental sensitivity to develop.

To assess whether children need letter–sound knowledge to develop phonological awareness, we classified participants according to whether or not they had succeeded on each of the three explicit-segmental-analysis tasks (Table 9). Success thresholds represented the chance level for the two multiple-choice tasks and a value of 42% for the phoneme-isolation performance (as explained previously). While 86% of the participants with low letter knowledge were above chance on the blending task, only 50% and 6% were above chance on the rhyme and phoneme-isolation tasks, respectively. When we looked at the percentages for rime- and phoneme-level items separately, we found that the percentage of participants with low letter knowledge who succeeded on the blending task was lower for phoneme than rime level items but was still high at 72%. On the phoneme-isolation task, none of the low-letter-knowledge participants succeeded on the phoneme-level items.

Discussion

How Are Segmental Sensitivity, Phonological Awareness, Vocabulary, and Letter–Sound Knowledge Related to One Another?

Our finding that vocabulary growth was a significant predictor of segmental sensitivity whereas letter–sound knowledge was not provides support for the lexical restructuring model (Metsala & Walley, 1998), which argues for vocabulary growth as a key driver of segmentation. We could argue that, if children's representations are segmented from infancy (as proposed by the accessibility account), we might still have expected to find a significant relation between vocabulary and segmental-sensitivity measures because of general ability and age-related factors (e.g., children with higher vocabulary scores may perform better on segmental-sensitivity measures because they are better at listening, following instructions, etc.). However, the fact that vocabulary predicted segmental-sensitivity performance over and above age but did not predict performance on explicit-segmental-analysis measures weakens this argument. The finding that most of the young nursery participants' responses on the four-choice mispronunciation task fit in the segmental or global response category ($p < .001$; see Figure 4) demonstrates that participants were not responding at random, which in turn suggests that they were able to cope with the task at hand. Furthermore, if the accessibility viewpoint holds true and children represent words segmentally from infancy, then we would also have expected to see much higher levels of performance on the segmental-sensitivity measures (which do not require any explicit knowledge of phonological segments) than those that we observed in the youngest nursery participants. That performance was relatively low and was found to increase over the age range that we studied supports the idea of segmental representation emerging developmentally, rather than being fully established from infancy.

The finding that letter–sound knowledge predicted explicit segmental analysis goes beyond the lexical restructuring model, providing support for the lexical restructuring model plus letters account (Carroll, 2004; Ventura et al., 2007), which proposes that, although letter–sound mappings may not be needed for segmenting the underlying representations themselves, they are important for the development of explicit phonological awareness. It is interesting that age did not emerge as a significant predictor in either model. This suggests that children's phonological knowledge is predominantly linked to how many words and how many letter–sound correspondences they know and not simply to their age.

Do Letter–Sound Mappings Need to Be Learned Before Phoneme-Level Phonological Representations Emerge?

Our results demonstrate that the majority of participating children with low levels of letter–sound knowledge (fewer than three letters known) scored above chance overall on all the measures of segmental sensitivity. This provides further support for the idea that, although letter–sound knowledge is correlated with segmental sensitivity (as shown in Table 4), it is not a prerequisite for segmentation to occur. The fact that the percentages of participants in the low-letter-knowledge group who were above chance remained relatively high (36–72%) when we considered phoneme-level items only rules out the possibility that the above-chance levels of segmental sensitivity that we saw in the low-letter-knowledge group were driven mainly by good performance on the rime-level items. In other words, children appear able to develop an emerging sensitivity to both rimes and phonemes in the absence of letter–sound knowledge. Ventura et al.'s (2007) study presented evidence of segmental sensitivity in adults who knew few or no letters. This study replicates this important result in a child sample.

Do We Need Letter–Sound Knowledge for Phonological Awareness?

The fact that letter–sound knowledge was a significant predictor of explicit segmental analysis suggests that the acquisition of letter–sound mappings may be important for the emergence of phonological awareness. However, our results also suggest that some measures of phonological awareness may be more strongly contingent on orthographic knowledge than are others. In particular, letters may be especially important for phoneme-isolation ability (cf. Carroll, 2004) but may not be needed for blending. The fact that children with very limited knowledge of letters can blend phonemes together may be explained by the fact that blending is arguably the least explicit of the phonological-awareness tasks. Studies have shown that blending is one of the earliest phonological awareness skills for children to master (Anthony, Lonigan, Driscoll, Phillips, & Burgess, 2003), and the extent to which children need to consciously access the phonemes in words to complete this task is unclear. Phoneme isolation, on the other hand, is arguably the most direct way of assessing children's knowledge of phonemes given that it asks children to state explicitly what the phonemes in a given word are. Phoneme isolation may therefore be a purer measure of conscious phonological awareness.

Theoretical Implications

The overall pattern of results (see Table 1) is consistent with the lexical restructuring model plus letters account (Carroll, 2004; Ventura et al, 2007), which suggests that, although phonological representations may become segmented without the need for letter knowledge, conscious access to the sounds in words for use in explicit phonological awareness tasks requires a grasp of phoneme–grapheme correspondences. This work builds on previous research in the developmental literature that has used similarity tasks to measure the development of phonological representations. Storkel (2002) found that although children store words from dense neighborhoods as phonemes, they represent words from sparse neighborhoods more coarsely, with the final sound represented by the manner of articulation (e.g., *boom* stored as /b/–/u/–/nasal/). Similarly, Carroll and Myers (2011) found that although both children and adults made manner classifications (i.e., judging words with shared manner of articulation as similar) as well as phonemic classifications, phonemic classifications became more frequent with age, and manner classifications tended to be in final position. Our finding that children's sensitivity to shared phonemes increases developmentally and is strongly associated with vocabulary size is consistent with this work.

Our study extends this body of research in two important ways. First, it included multiple-choice tasks that are potentially more powerful than forced-choice tasks for trying to determine whether or not children are using phonemic similarity relations. This is because in a forced-choice task (where a participant is asked to decide if an item is similar or not to another item) there is no set threshold for determining whether something is similar or not. For example, a literate adult who presumably represents words at the phoneme level might consider the words *beach* and *dish* to be similar based on global features. For example, they both start with a stop and end with an affricate/fricative (Carroll & Snowling, 2001). But when asked to choose which of two words is most similar to *beach*—*bean* or *dish*, they might judge *bean* to be more similar on the basis that it has two shared phonemes whereas *dish* has none. In other words, while a forced-choice task tells us whether two items are classed as similar or not, it does not tell us directly about graded similarity, that is, which type of similarity relation is considered to be most important. In our study, we were able to assess child participants' sensitivity to phonemic similarity over and above global similarity, allowing us to draw stronger conclusions about the development of segmental sensitivity over time.

This study also extends existing work by breaking down the measurement of segmental sensitivity into sensitivity at the onset–rime versus phoneme level—two levels that are proposed as emerging sequentially in the lexical restructuring model (Metsala & Walley, 1998). In this way, we were able to test the prediction made by psycholinguistic grain size theory that phonemes only emerge in children's representations once letter–sound correspondences have been learned. We presented evidence that preliterate children's representations are segmented beyond the onset–rime level—with some participating children who knew fewer than three letters showing success on measures of phoneme-level sensitivity, something that cannot be carried out on the basis of comparing onsets or rimes only. The fact that preliterate children can make phonemic classifications when global similarity has been controlled for therefore contradicts Ziegler and Goswami's (2005) proposition that phonological representations only become stored in terms of shared phonemes once children learn the correspondences between letters and sounds.

We made a distinction between the accessibility and emergent viewpoints. However, it is possible that phonological development resembles a hybrid of both accounts, as proposed in the developmental framework for processing rich information from multidimensional interactive representations or the PRIMIR framework (Werker & Curtin, 2005; see also Dietrich, Swingley, & Werker, 2007; Swingley, 2009), where early specificity at the phone level precedes gradual emergence of contrastive phonemic representation. There are two key differences between PRIMIR and the lexical restructuring model plus letters account: (a) in PRIMIR, representations are predicted to be rich in detail from infancy, unlike the vague early representations of the lexical restructuring model, and (b) within PRIMIR, letters are proposed to "sharpen up" emerging phonemic categories, whereas in the lexical restructuring model plus letters account, phonemic representation is proposed to emerge independent of literacy. On the one hand, PRIMIR seems a more promising candidate, given that it accounts readily for the early specificity demonstrated in infant studies. However, researchers need to consider how the predicted orthographic sharpening of phonemes might be reconciled with our finding that phonemic representation occurs in the absence of letter knowledge. Given that PRIMIR predicts that letters play only a minor role in the tightening up of phonemic representation rather than in its formation, right at the end of the process of phonemic emergence, it is likely that our measures of segmental sensitivity were not sufficiently sensitive to measure this fine tuning. To empirically test this notion of phonemic representation being sharpened by letters, a more sensitive set of measures needs to be developed, with prior theoretical consideration given to exactly what that sharpening might involve. Computational modelling of the potential influence of phonemic labels on phonological representations, informed by Lupyan's (2012) model of language augmented thought, might provide a useful starting point.

Methodological Implications: Similarity Judgments as a Probe Into the Lexicon

Two key issues have clouded the debate around phonological development: (a) ambiguity regarding measurement at the phone versus the phoneme level (Ainsworth et al., 2016; Ziegler & Goswami, 2005) and (b) differences in the degree of explicit knowledge required when researchers attempt to measure segmental sensitivity. In our study, we addressed both these issues by measuring segmental sensitivity at the phoneme (rather than phone) level using novel tasks that did not require any explicit knowledge of phonological structure alongside traditional phonological awareness tasks requiring explicit segmental analysis.

Previous studies that failed to find a relationship between vocabulary size and infants' ability to detect mispronunciations (Swingley & Aslin, 2000; Werker, Fennell, Corcoran, & Stager, 2002) concluded that "spoken vocabulary is not the driving force behind the accurate phonetic specification of words" (Swingley & Aslin, 2000, p. 162). However, as highlighted by Swingley and Aslin, these findings measured sensitivity to phonetic detail rather than representational segmentation, and so they did not rule out the possibility of children's representations becoming increasingly phonologically segmented as their vocabularies grow. In our study, where we used measures designed to probe phoneme-level segmentation rather than phone-level accuracy, we found evidence to support vocabulary-driven restructuring. Our study therefore highlights the need for researchers to differentiate between the two types of measurement when they investigate children's phonological representations.

The second issue relates to the level of explicit phonological knowledge that researchers require when attempting to measure segmental sensitivity. We have shown that although performance on tasks requiring explicit awareness of segmental phonological structure is associated with letter–sound knowledge, participants' performance on implicit segmental-sensitivity tasks revealed the existence of segmental-phonological representations that are independent of orthography. These findings underline the need for researchers to make phonological tasks as implicit as possible when they attempt to probe the level of segmentation of the representations themselves.

It is worth noting that, although a key aim of our study was to design measures of phonological representation that do not require an explicit awareness of sound segments, the factor loadings presented in Table 5 suggest that some tasks may draw upon explicit knowledge at least to some extent. In particular, the incomplete-word task loaded substantially onto both factors. This suggests that although children's guessing what a puppet wants upon hearing an initial sound does not require them to have explicit knowledge of sound structure, such knowledge can boost their performance. This boosting of performance may be due to the increased salience of individual phonemes for children with higher levels of phonological awareness. If, for example, children have had lots of experience of phonological-awareness training activities where the initial phoneme of a sound is emphasized, for example, "Can you find me the sssss-nake?" then the initial phoneme will be especially salient and the segmental response is more likely to jump out at the children. The fact that the incomplete-word task loaded more highly onto the Explicit Segmental Analysis factor in comparison with the other tasks might have been due to the fact that it is the only segmental-sensitivity task that involved linking an individual segment to a word; the other three tasks all involved comparing CVC word forms to one another. It may be that the salience of individual phonemes brought about by phonological awareness has a greater effect on tasks that involve individual sound segments because these are closer in nature to the kinds of phonological-awareness training children receive in school. The key implication of this is that although the measures were not able to entirely separate implicit and explicit knowledge of the phonological segments within words, they showed the importance of researchers' limiting the amount of explicit knowledge they require from children when they try to measure children's phonological representations at an early age.

Implications for Educational Practice

Our study has important implications for the early identification of phonological difficulties in children. Although the cause of developmental dyslexia remains a controversial topic, many authors have suggested that the quality of children's phonological representations may be implicated (Fowler, 1991; Ramus, 2003; Snowling, 2000; Wolf et al., 2002; although see Dickie, Ota, & Clark, 2013, for evidence to the contrary). The phonological deficit hypothesis proposes that the phonological representations of children with dyslexia may be underspecified in comparison with those of children without dyslexia (Ramus, 2003; Snowling, 2000). If the quality of phonological representations is a potential marker for children at risk of phonological difficulties and related problems when they are learning to read, it is therefore important to have measures that can probe children's representations at an early age (e.g., Claessen, Heath, Fletcher, Hogben, & Leitão, 2009).

Previous studies investigating the early identification of phonological impairment have tended to use mispronunciation detection tasks (e.g., Claessen et al., 2009) or measures of phonological awareness (e.g., Catts, Fey, Zhang, & Tomblin, 2001; Hogan, Catts, & Little, 2005; Lonigan et al., 2000). The findings of our study present important implications for the use of these measures. We have demonstrated that although phone-level measures used in infant studies suggest adultlike levels of detail in children's early representations, children's performance on segmental sensitivity measures at the phoneme level suggest that phonemic representation emerges only gradually. For measuring a phonological deficit that might impair a child's chance at later reading success, it is representation at the phoneme level that is of interest (Fowler, 1991). Given that mispronunciation-detection tasks measure accuracy at the phone level rather than segmentation at the phoneme level (Ziegler & Goswami, 2005), they may not therefore be suitable for picking up on the differences in the segmentation of children's phonological representations proposed to predict problems with phoneme awareness and later reading performance (Fowler, 1991).

The second type of measure often used to identify children at risk of later reading performance—phonological awareness—is limited in terms of the age at which it can be diagnostically useful. Although research has shown phonological awareness tasks to be effective indicators of later reading skills in children (Catts et al., 2001; Hogan et al., 2005; Lonigan et al., 2000), our findings suggest that phonological awareness performance at the phoneme level is dependent on letter–sound knowledge. When children score poorly on a phoneme-awareness task, it is therefore difficult to assess whether this is because they have an underlying phonological deficit or because they have yet to gain the letter–sound knowledge required to perform the task. Poor performance in young children could also be due to the metacognitive demands of the task being too high. The segmental-sensitivity measures used in our study provide an alternative method for assessing the precursors of phonological difficulties with two key advantages. First, the tasks measure phoneme- rather than phone-level representation, which as we discussed above, is the level predicted to be related to reading difficulties (Fowler, 1991). Second, the tasks do not require any explicit awareness of phonological structure. This means that they are less demanding metacognitively and do not depend on orthographic knowledge. The tasks therefore have the potential for identifying phonological impairment earlier than has been previously possible. Given the importance of early intervention for supporting children with reading difficulties (Strickland, 2002; The National Strategies Primary, 2009), we recommend further investigation into the feasibility of using these measures for early identification of phonological difficulties for future work.

Limitations and Future Work

Our study has important implications for the measurement of phonological representations and the early identification of phonological impairment. There are, however, a number of limitations that need to be considered. First, the cross-sectional nature of the study precludes our drawing conclusions about causality. Although our study allowed us to explore the associations between key variables of interest and to assess the theoretical account with which they are most consistent, we are unable to confirm whether one variable drives change in another. We therefore recommend a longitudinal investigation of children's performance on these measures to allow stronger conclusions about the trajectory of phonological development to be made.

Another limitation of the study is the relatively low proportion of variance in segmental sensitivity explained by the first regression model. This was likely due to the implicit nature of the segmental-sensitivity measures. These measures are less direct in terms of the instructions given to children. For example, they asked participants to make sounds-like judgments without specifying the criteria that we wanted them to use to judge the interstimulus similarity. The lack of any explicit reference to phonological segments was a deliberate and necessary aspect of the design of the tasks to eliminate the need for participants to have explicit phonological knowledge and to limit metacognitive demands on the participants. However, the lack of explicit criteria means that children are free to make a global or segmental judgment—either fulfils the demands of the tasks. This inevitably leads to more noise in the data than would occur on a more explicit task with only one correct answer. In our study, there was anecdotal evidence that participants were sometimes responding to cues that were not phonological (e.g., semantic cues or physical appearance). For example, one child who chose *phone* on the mispronunciation-reconstruction task hovered her hand above the phone even before she heard the stimulus *tain*, suggesting that she simply liked the picture. Even if we could be sure that children were always responding on the basis of "sounds-like" similarity, there is also likely to be noise associated with the similarity metric used to match the global versus phonemic choices. Although the global similarity metric provides a useful estimate of the global similarity between phonological forms (Byrne & Fielding-Barnsley, 1993; Carroll & Snowling, 2001), it is unlikely to be exact given its derivation from adult judgment data that are inherently subjective (Kessler, 2005) and given that it does not take into account the effects of coarticulation. Future research might therefore explore ways to minimize the noise associated with the similarity classification tasks—for example, through detailed error analysis and exploration of more sophisticated similarity metrics.

Finally, it is important to note that our study took place in England, where children receive explicit instruction in letter–sound knowledge and phonological awareness relatively early. Cross-cultural studies are therefore needed to evaluate the extent to which our pattern of results is generalizable.

Conclusion

In conclusion, our study tested predictions made by key theoretical accounts of phonological development using novel measures of segmental sensitivity alongside traditional measures of explicit phonological awareness. We presented evidence that, although letter–sound knowledge may be important for success on most explicit-segmental-analysis tasks, it may not be required for phonemic sensitivity to emerge. We found evidence of children with very limited knowledge of letters succeeding on tasks measuring implicit sensitivity to phonemes. The results are consistent with the view that oral language experience predominantly drives lexical restructuring and that phonemes may emerge within the lexicon in the absence of literacy (Ventura et al., 2007). This study highlights the ability of segmental sensitivity measures to detect the effects of lexical restructuring independent of orthography.

Final revised version accepted 11 October 2018

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix S1. Target Items and Matching Statistics.
Appendix S2. Summary of Target Measures.
Appendix S3. Effect Sizes for All Between-Group Comparisons.

Appendix: Accessible Summary (also publicly available at https://oasis-database.org)

New Tasks Shed Light on Children's Knowledge of the Sounds in Words

What This Research Was About and Why It Is Important

Although researchers generally agree about how children store information about the sounds in words, there is less agreement about how children *develop* their knowledge of sounds. One reason for this lack of agreement is that tasks used in research have been too difficult for very young children to perform. To address this challenge, for this study, the researchers developed new tasks in order to explore young children's knowledge of sounds in a way which has not been possible before. These new tasks were designed to be as easy for young children to complete as possible. The researchers found that as children learn more words, the way that they store the sounds in these words changes. As children's vocabularies grow, the children begin to store words in terms of the individual sounds within them, rather than based on the overall sound pattern of the word.

What the Researchers Did

- The researchers tested 88 children age 3 to 5 years in England. All children were native speakers of English enrolled in nursery (daycare) or reception (kindergarten) classes.
- The researchers developed new tasks to measure young children's knowledge of the sounds in words.
    - Some of the tasks involved children making judgments about how similar words are to each other. In one task, children heard a puppet mispronounce a word and then had to guess which picture the puppet was trying to say, by choosing the picture the word sounded the most like. For example, the puppet said *tet*, and children had to decide whether he was trying to say *ten*, *tape*, *teeth*, or *sun*.
    - Other tasks involved children choosing which picture matched an individual sound. For example, children were shown four pictures (e.g., of the sun, rain, a pan, a coat) and were asked which one rhymed with a word spoken by a researcher (e.g., "Which one rhymes with run?").
- The researchers also measured children's knowledge of letters and vocabulary.

What the Researchers Found

- As children learn more words, the way that they store the sounds in words changes. As children's vocabularies grow, they begin to store words in terms of the individual sounds within them, rather than the overall sound of the word.
- Until children learn about letters, they may not be aware that they have this knowledge of the individual sounds within words. However, once they learn about letters, they become more consciously aware of the way that words are structured.
- The new tasks were able to measure children's knowledge of the sounds in words without the child needing to know anything about spelling (how letters relate to sounds).

Things to Consider

- The use of several tasks—those that rely on children's knowledge of letters and those that do not—helped the researchers to test different theories of how children learn about the sounds in words.
- The findings generally support the idea that vocabulary growth changes the way in which children store words.
- The kinds of tasks employed in this study might be useful when identifying potential problems with the way that some young children store the sounds in words, which might lead to reading and writing difficulties for these children later on.
- Further research is needed to see if these tasks might be used for early identification of reading problems.

How to cite this summary: Ainsworth, S. L., Welbourne, S., Woollams, A., & Hesketh, A. (2019). New tasks shed light on children's knowledge of the sounds in words. *OASIS Summary* of Ainsworth et al. in *Language Learning*. https://oasis-database.org